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Field Emission Studies for Microwave and Optical Wave Generation

K. Yokoo, K. Okamura, H. Mimura, O. Yilmazoglu, D. Arslan, H. Hartnagel, and H. Ishizuka

Abstract - **We have proposed hybrid electronics based on solid-state and vacuum electron devices for an application to relatively high power and high efficiency active devices in microwave and optical wave regions. The new electronics provides a bunched electron beam in these frequency regions and a fine beam with an extremely low electron temperature by the combination between field emission and semiconductor technologies.**

The paper describes the experiments of microwave electron emission from a GaAs field emitter caused by a traveling dipole domain originated by the Gunn effect in the compound semiconductor emitter and resonant tunneling emission from a GaAs/AlAs quantum structure.

In addition, the paper describes Smith-Purcell radiation in optical wavelength using a field emitter arrays.

I. INTRODUCTION

The topic of vacuum microelectronics has been receiving a great deal of attention in the field of electron devices for the past ten years. A field emission display (FED) is a major subject in development of vacuum microelectronic devices due to an extremely large market for image media in the 21st century. However, the vacuum microelectronics is still the center of interest in high frequency electronics, because it provides relatively high power and environment hard electronics due to the advantages of vacuum as a charge transport medium. In addition, vacuum devices are generally possible to apply energy recover technique for spent electrons resulting in high efficiency.

We have proposed generation of a modulation electron beam at the frequency of microwave and in excess of millimeter wave regions and a fine electron beam with a high brightness and an extremely low beam temperature from a field emitter arrays (FEA) by applying a solid-state device technology to FEA [1]. The modulation beam provides a high efficiency in an electron beam device as expected from the operation of klystron and traveling wave tube. The cold electron beam is applicable to optical wave and further high frequency devices. These hybrid electronics based on a combination technology of solid-state and vacuum electron devices were first proposed to develop a monolithic device of FEA and an active device to control the emission current of FEA for an application to FED [2]. Then, the operation frequency is limited around several tenth and hundreds MHz. However, the concept has been expanded in the operation frequency up to microwave and THz wave regions not only by accommodating microwave transistor and applying the Gunn effect in a compound semiconductor to a FEA, but also using photomixing technique to a semiconductor FEA [3]. The cold beam without energy dispersion is produced by using resonant tunneling behavior in a quantum structure [4].

The paper describes the basic experiments of the proposals, in which microwave electron emission based on a traveling dipole domain originated by the Gunn effect in a GaAs field emitter and resonant tunneling electron emission from a GaAs/AlAs quantum structure are discussed. Finally, the paper describes Smith-Purcell radiation in optical wavelength using a field emitter arrays.

II. ELECTRON EMISSION FROM GUNN DOMAIN

When a voltage higher than the threshold voltage is applied on a compound semiconductor diode, traveling dipole domains are generated in the diode and Gunn oscillation takes place. If the emitter tips of FEA are constructed from a compound semiconductor such as GaAs and InP and biased by suitable electric field, traveling domains are generated in the emitter and the accumulated charges in the domains are emitted into vacuum when they reach the emitter surface. The frequency of the pre-bunched electron emission is determined by the emitter size and configuration same as the Gunn diode and covers microwave and millimeter wave regions.

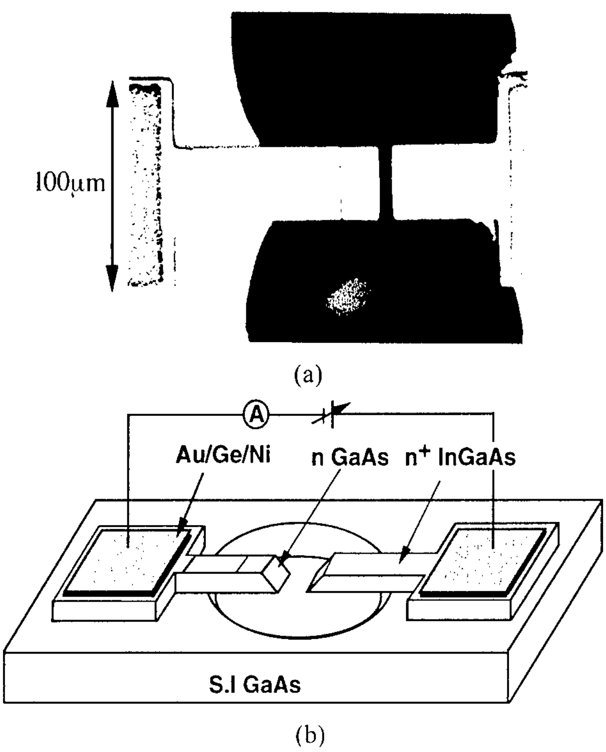

Fig. 1: SEM image (a) and its schematic structure (b) of the GaAs lateral field emitter

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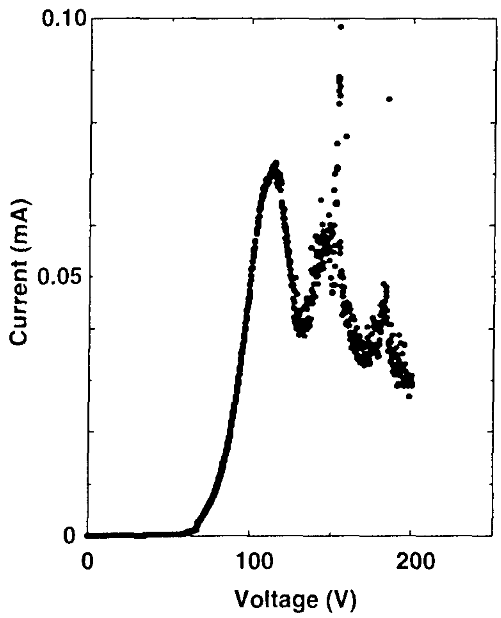
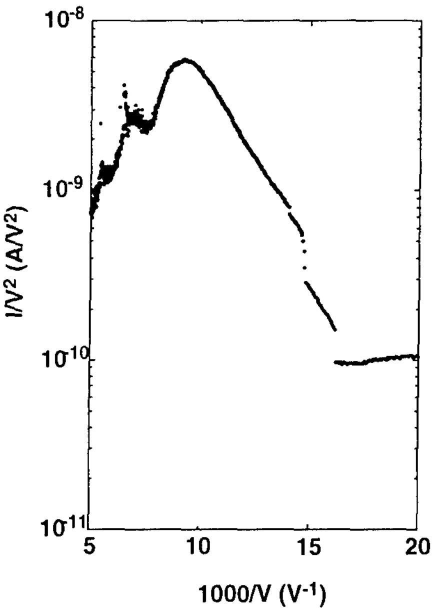


(a)



(b)

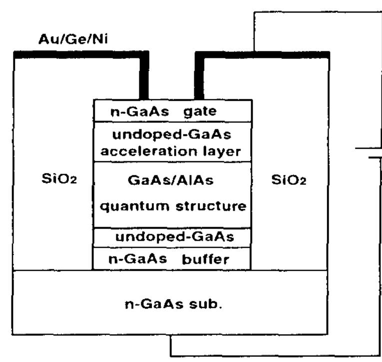
Fig. 2: Emission current-voltage characteristic of the GaAs emitter (a) and its Fowler-Nordheim plot (b)

We fabricated the GaAs field emitters with lateral structure as the first step of experiments. Figure 1 (a) and (b) show a SEM image and a schematic structure of the emitter, respectively, which are fabricated by micromachining technique using anisotropic etching of GaAs [5]. The doping concentration of the GaAs emitter is $1\times10^{15}cm^{-3}$, which satisfies formation of the traveling dipole domains in the emitters. In addition, we fabricated the emitters with doping concentration of $1\times10^{18}cm^{-3}$ to compare the emission characteristics of the emitters.

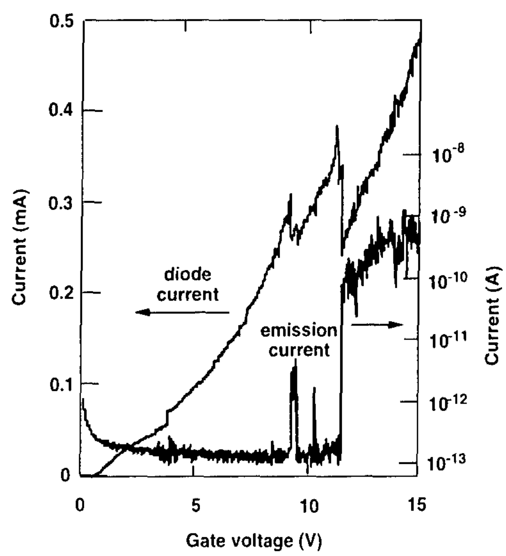
Figure 2 (a) and (b) show a current-voltage characteristic of an emitter and its Fowler-Nordheim plot, respectively. Electron emission occurs at about 60 V and is characterized as field emission from the slope of the straight line in the F-N plot at the low voltages less than 100 V. However, the emission current reaches the maximum value at about 110 V and it becomes unstable at the voltages above, as shown in Fig.2 (a). The current voltage characteristic of the emitter is quite similar to that of a bulk GaAs diode with Gunn oscillation except the threshold voltage around 60 V in the characteristic which does not appear in a conventional Gunn diode. On the other hand, the emission current increases monotonically with increase in voltage in the emitter with the doping concentration of $1\times10^{18}cm^{-3}$, though there is the threshold voltage in its characteristic, as same as the emitter shown in Fig.2 (a). We are expecting that the electron emission is characterized by the field emission of accumulated electrons in the traveling dipole domains in the emitter.

III. RESONANT TUNNELING EMISSION

A high brightness and low emittance electron beam is very important for applications to optical wave and further high frequency electron beam devices such as a tabletop free electron laser (FEL) at optical wave and X-ray regions [6]. A cold electron beam without energy dispersion is produced by applying the resonant tunneling effect in a quantum structure to an electron emitter.



(a)



(b)

Fig. 3: Schematic diagram of a resonant tunneling cathode with GaAs/AlAs quantum-well (a) and its diode and emission current characteristics (b)

Figure 3 (a) shows the schematic diagram of a resonant tunneling cathode with GaAs/AlAs quantum-well structure fabricated by molecular beam epitaxy. Figure 3 (b) shows the diode and emission current characteristics of the cathode as a function of gate voltage. The emission current increases abruptly at some threshold voltages and has several peak values following the diode current of resonant tunneling through the sub-bands in the quantum well. The resonant tunneling electron emission is expected to be narrow enough in energy spread of emitted electrons, which improves drastically the resolution of electron microscope and electron lithograph. In addition, these cold electrons enable to produce an extremely low emittance beam and realize a new electronics such as an electron channeling free electron laser at X-ray region [7].

IV. SMITH-PURCELL RADIATION

A tabletop FEL is an attractive application of FEA, because the compact radiation system covers almost all wavelength above millimeter and submillimeter. Smith-Purcell (SP) radiation was examined at optical wavelengths of 350-750 nm by using FEA as a first step of relatively high energy beam applications of FEA.

Both single-gated Si-FEA with the number of emitter tips from 1 to 7, and double-gated FEA with 640 tips are used in the experiments, as one of SEM image of the emitter is shown in Fig.4. An electron beam with the current higher than 10 μA is produced from FEA and is accelerated up to 45 keV in energy by the stabilized Van de Graaff generator. The energetic electron beam flows on a grating after passing through the slit with 1 mm in width provided just in the front of the grating. The grating used in the experiments is the aluminum-coated holographic replica with the period of 0.56 μm. Optical radiation was measured in the diffraction angle of 80° from the center of the grating.

Figure 5 shows the power spectra of radiation for several beam energy. The spectra showed good agreement with the theoretical prediction of the SP radiation, as shown in Figure 6. Diffraction orders of the radiation were –2, -3 and –4 for beam energy around 45 keV and the orders from –3 to –5 were observed at the energy around 20 keV The radiation was relatively stable over several minutes reflecting the stable electron emission from the FEA.

These radiation experiments assure the application of FEA to a compact FEL at optical wavelength.

V. CONCLUSION

The paper described the experiments of the microwave electron emission caused by traveling dipole domains in a GaAs field emitter and the resonant tunneling emission from GaAs/AlAs quantum structure. These combination technology of solid-state and vacuum electron devices provides a new electronics especially in the field of high frequency electronics. Finally, the paper described Smith-Purcell radiation at optical wave length using a field emitter arrays and a sub-micron pitch grating which are fabricated by micromachining technique. The experiments show that FEA provides a tabletop tunable radiation source covering the wavelengths of optical and X-ray regions, which is widely applicable in the material and the biological science.

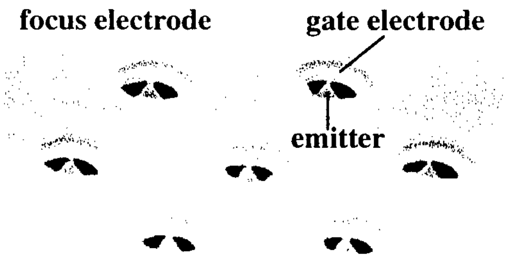


Fig.4: SEM image of Si gated-FEA used in the experiments of Smith-Purcell radiation

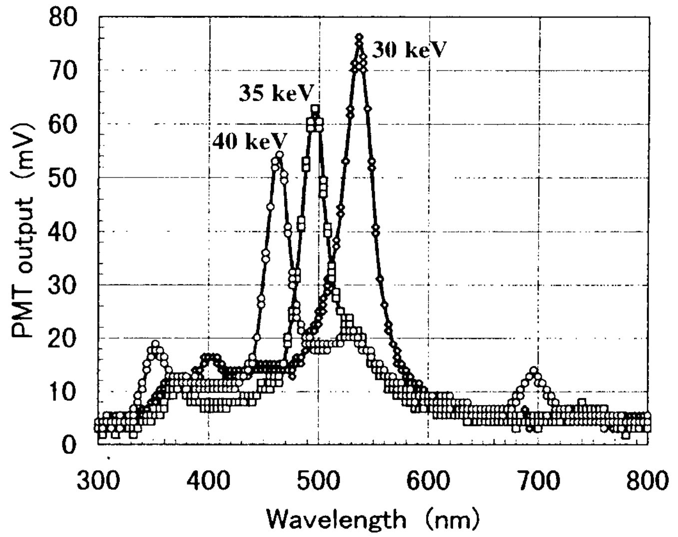


Fig. 5: Power spectra of Smith-Purcell radiations for several beam energy

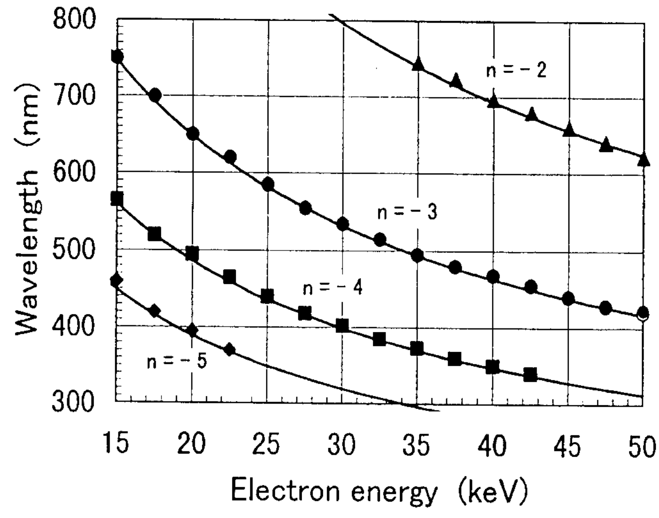


Fig. 6: Radiation wavelength for several diffraction orders observed at the diffraction angle of 80° from the center of the grating

Acknowledgment

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